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Observation of Nonlinear Reflectivity from InSb Surface and Optical Switching Application

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ABSTRACT

We report the observation of external switching of the reflectivity from the InSb surface by a plasma enhanced absorption mechanism. A HeNe laser and a pulsed CO_2 laser were used as probe beam and switching beam respectively. We also report reflectivity switching initiated as a result of a thermal effect in the InSb surface.

1. INTRODUCTION

Narrow bandgap semiconductors with large optical nonlinearities have been studied extensively in recent years. Optical-optical switching that utilizes the optical nonlinearities in semiconductors, such as InSb, have been reported in the literature.[1] Optical bistability is achieved in devices fabricated as Fabry-Perot resonators. The resonators depend upon the transmission of light through the material and require interference between two rays from parallel reflective surfaces of the resonator cavity. Therefore, the devices require materials that have two high quality surfaces and a nearly defect free crystal bulk. Optical switching with InSb materials in Fabry-Perot resonators present several difficulties, the cavities demand highly monochromatic light near bandgap and are easily disturbed by temperature fluctuations.

In order to make an optically addressed device that avoids the above disadvantages, it would be desirable to be able to switch optical reflection from a single surface using general light sources. Precedent exists for surface reflectivity switching.[2] Prior devices used switching photon energies well above bandgap and depended on reflectivity changes that occur through the excitation of a large number of carriers at the surface by an intense pulse. Most materials are damaged by giant pulse operations. In the present study we investigated external switching of the reflectivity of HeNe radiation from InSb surfaces. Two photon absorption from a CO_2 laser was used to pump the reflectivity change. The mechanism for the reflectivity changes is attributed to electron-hole plasma enhanced absorption.

2. THEORETICAL BACKGROUND

In order to study the reflectivity switching from a nonlinear optical material, the Fresnel equations which describe the fraction of incident energy reflected at a plane surface[3] need to be considered. These equations are functions of the refractive index, the incident angle and the polarization of the incident light.

Regarding the incident light as consisting of plane harmonic waves, where the electric field is given as $E = E_0 e^{i(kr-wt)}$, reflection coefficients for two polarization components, p and s, may be written in the form:

$$\text{s wave:} \quad \frac{E_R}{E} = \frac{\cos\theta-(n^{*2}-\sin^2\theta)^{1/2}}{\cos\theta+(n^{*2}-\sin^2\theta)^{1/2}}$$

$$\text{p wave:} \quad \frac{E_R}{E} = \frac{n^{*2}\cos\theta-(n^{*2}-\sin^2\theta)^{1/2}}{n^{*2}\cos\theta+(n^{*2}-\sin^2\theta)^{1/2}} \qquad (1)$$

where θ is the incident angle and n^* is the relative refractive index n_2^*/n_1^*. For the case where light is incident from air, $n_1 = 1$, and then $n^* = n_2^*$. In general n^* is a complex number given as $n^* = n + ik$, where the real part, n, is the ordinary refractive index, and the imaginery part, k, is related to the absorption coefficient, α, by $\alpha = 4\pi k/\lambda$. Therefore, it is clear that changes either in n or k can give rise to measurable changes in reflection.

InSb has been found to exhibit an intensity-dependent refractive index[4]

$$n = n_0 + n_2 I = n_0 + \Delta n \qquad (2)$$

where n_0 is dark index, $n_2 I$ is the intensity-dependent refractive index (note: n_2 is the rate of change of index with intensity and is different from the n_2^* in equation (1)) and I is the incident light intensity. The change in the refractive index Δn is directly proportional to ΔN, the excess carrier density induced by the radiation, and given by $\Delta n = \sigma\Delta N$. The coefficient of proportionality σ is a function of the radiation frequency ω as shown by[4]

$$\sigma = \frac{2\pi|\bar{\mu}|^2}{\hbar n_0(\bar{\omega}_0-\omega)} \qquad (3)$$

where μ is the effective electric dipole moment of the transition, ω_0 is the center frequency of the transition. The bar over μ and ω_0 is indicative of the effective average value. The proportionality factor σ, hence n, shows a strong increase as ω approaches ω_0, a condition that is so-called "bandgap resonance". Using radiation with frequency near the bandgap, one could change the nonlinear refractive index, and give rise to a significant change in the reflection. It was previously reported[5,6] that for infrared radiation, σ is negative for InSb and as seen in equation (2) would cause a decrease in n with an intense pump beam.

The total absorption loss coefficient is given by[5]

$$\alpha = \alpha_0 + \alpha_e + (\sigma_p + \sigma_n)\Delta N \qquad (4)$$

where α_0 is the band-edge absorption coefficient, α_e is an extra absorption term that takes into account losses due to scattering, and the final term quantifies free-carrier absorption with σ_p and σ_n as the hole and electron absorption cross sections, respectively. These three terms, and in particular the final term, could be modified by an intense pump beam. The excess carrier density ΔN generated by the pump beam could give rise to a significant increase in absorption. Thus the reflected intensity of a probe beam could be modified upon radiation of the sample with the pump beam.

Thermal effects also need to be considered. In general, the InSb energy bandgap decreases with an increase in temperature that can be caused by either probe or pump radiation. This results in increases in α_0, $\sigma(\Delta n/\Delta N)$ and the linear refractive index n_0. The change in reflection for InSb can be anticipated from both optical and thermal effects, and the changes can be both positive and negative:

1. An increase in α and n_0 can cause an increase in the reflection.
2. An increase in ΔN and σ (σ is negative for far infrared radiation) cause a decrease in the reflection.

Both of these two effects are competitive and the resultant reflectivity change is their algebraic sum.

3. EXPERIMENTAL

The samples used are n-type InSb wafers ($N_D = 2x10^{14}$ cm^{-3}) with one polished surface and thicknesses of 457 μm and 711 μm. The experiments were performed at room temperature with the apparatus shown in Fig.1. The sample was illuminated by a cw HeNe laser, operating at a wavelength of 6328 Å with ~ 1 mm^2 spot. The incident angle was aimed slightly off the normal direction and the reflected power was monitored by a photomultiplier.

This system was used to demonstrate that illumination of an InSb surface with a 10 μm light pulse (two photon excitation, as pump beam) from a CO_2 TEA laser would cause switching in HeNe laser reflection. The CO_2 pulse, attenuated by a SF_6 gas cell with ajustable pressure, was incident on the sample with its illumination overlapping the region illuminated by the HeNe beam. The intensity at the InSb surface was ~1 Mw/cm^2. A fast pyroelectric detector was used to sense part of the CO_2 pulse signal from a ZnSe beam splitter which was used to trigger the oscilloscope.

Fig.2(a) is the CO_2 laser pulse. Fig.2(b) shows the reflected signal of the HeNe light that was switched out by the CO_2 pulse with the 457 μm thick sample. The rise time of the reflected HeNe pulse was approximately equal to that of the CO_2 pulse and the contrast ratio was observed to be ~1:4.

Fig.3 is the scope display at a larger time scale. The lower trace is the incident CO_2 pump pulse, the upper trace is the inverted reflected HeNe probe signal. The reflected HeNe probe beam has two components separated by a time delay and with opposite phases. The temporal dependence of the relected pulse indicates that the refractive index change contains a fast response attributed to direct optical transitions and a slow component attributed to thermal warning of the crystal; i.e., the second pulse is likely explained as due to rapid heating of the InSb from the absorption of the CO_2 radiation.

An effort was made to switch a cw CO_2 laser by the CO_2 pulse. Initial investigation was incidence-reflection characteristic of the InSb surface for cw CO_2 radiation. The curve is shown in Fig.4. The sample used was 711 μm thick. It is notable that the reflected power increased rapidly as the input power increased beyond 600 mw. This self-switching behaviour might be applied to external switching, and an experiment addressed this question. The sample was optically biased by the cw CO_2 laser at ~600 mw input power, and the pulsed CO_2 laser, as an external switching beam was aligned such that the pulse would illuminate the same spot on the sample as the cw beam. In this condition only a slow reflected signal was observed which indicated a thermal switching effect. The signal was positive, consistent with the switching-up character of the cw beam radiation.

4. DISCUSSION

Using the Fresnel equations, we calculated the dependence of the reflectance of InSb on the incident angle, refractive index and absorption coefficient. Since at near normal incidence the p and s waves have similar behaviour, only the p wave was considered. Fig.5 shows the plots of the reflectance versus incident angle, using a wavelength of 6328 Å (HeNe laser). Two sets of curves with different n and k are shown in (a) and (b) respectively. The same kind of plots for reflected 10 μm CO_2 radiation are shown in Fig.6(a) and (b).

From the data in Fig.2 it is seen that the change in the reflected signal obtained using the HeNe probe beam is positive, and it could result from either an increase in refractive index, Δn, or the absorption factor, Δk. The simulations in Fig.5(a) show that for HeNe light only a positive change in n can cause an increase in reflection, and the situation is the same for CO_2 light as is shown in Fig.6(a). However, previous work has shown that Δn induced in InSb by CO_2 radiation is negative.[6] Thus, the switching mechanism is most likely an optical enhancement of absorption. As shown in equation (4), the absorption could be enhanced significantly by the excess free carriers which are generated by the external radiation, and by extra scattering losses. In our circumstance the CO_2 pulse induces an electron-hole plasma and "writes" the absorption enhancement on the InSb sample, and the HeNe probe beam "reads" this change and yields the positive changes as observed in the reflection. Since two photon absorption coefficient is small, the pump beam has to be operated at relatively high power.

For InSb, the imaginery part of the refractive index, k, is 1.799[7] at the wavelength of 6328 Å. Thus, even a small percentage in k will give rise to a sizeable change in the reflection. It can be seen from Fig.5(b), $\Delta k = 1.5$ will cause a 25% increase in the reflection which we observed. On the other hand, the k is $\sim 9 \times 10^{-4}$ for the 10 μm radiation[7], as shown in Fig.6(b), any measurable reflectance change requires a huge percentage change in the absorption. This might be the reason for the unsuccessful use of the cw CO_2 laser as the probe beam.

In our experimental data, thermal induced switching was charactered by a time delay and slow rise time (~1 ms). The signal could be either positive or negative and depended on the balance between two opposite effects (see section 2).

5. CONCLUSIONS

External switching of HeNe reflection resulting from plasma enhanced absorption in room temperature InSb has been demonstrated. The advantages for this mode of operation are as follows:

1. The switching only occurs near the surface, it does not require a Fabry-Perot cavity.
2. The probe beam does not require bandgap resonance hence any visible light could be used.
3. The switching takes place at room temperature thus a serious restriction for practical applications is lifted.

An associated thermal effect has also been studied, however it appears that this effect is too slow for practical application.

6. ACKNOWLEDGMENT

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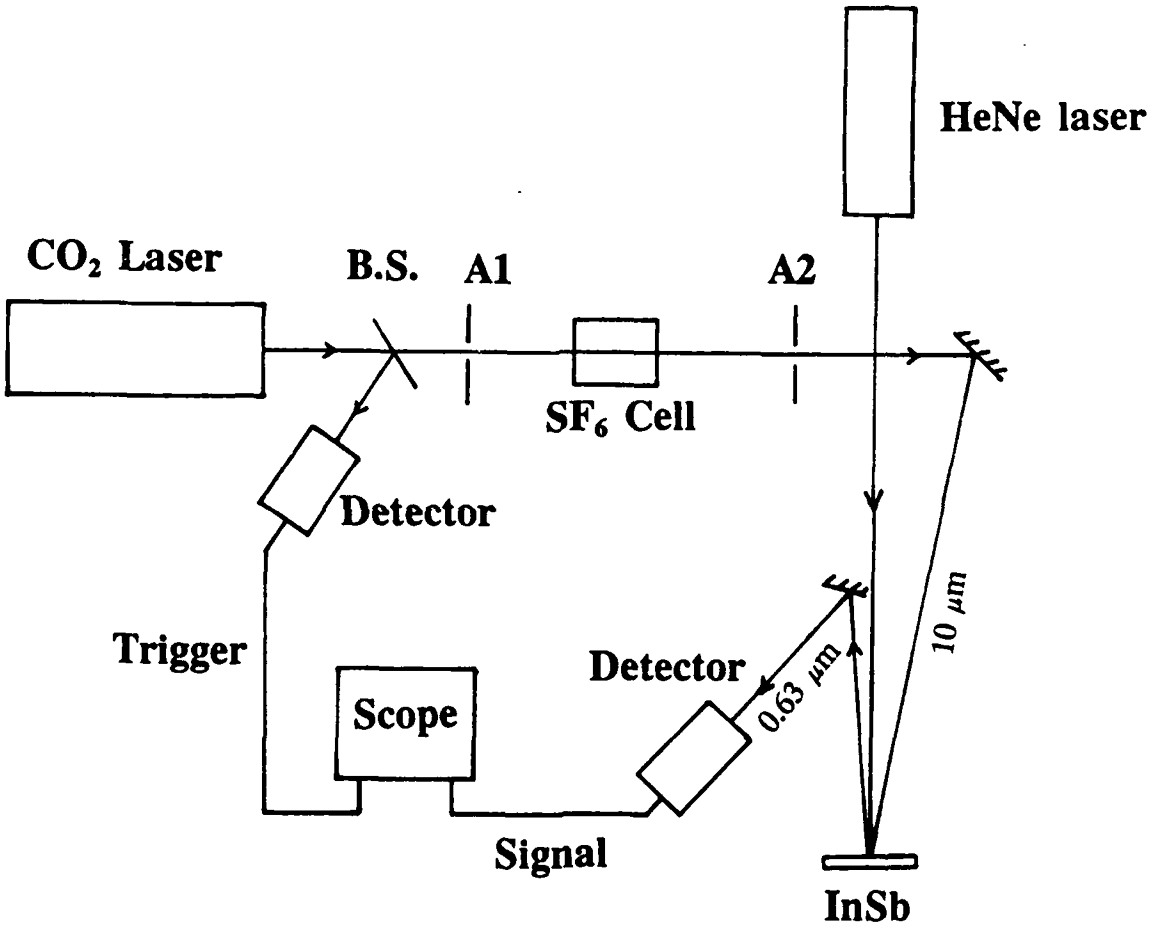
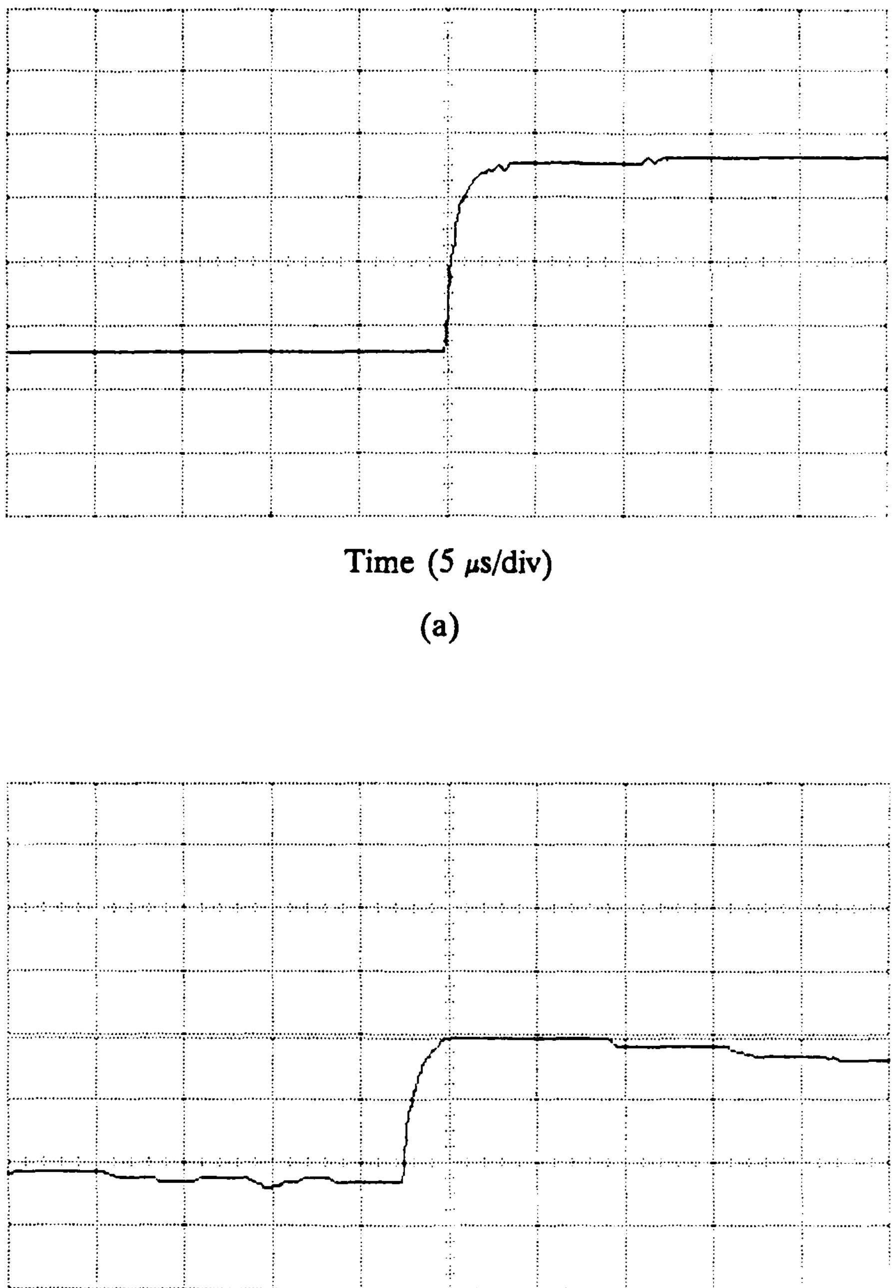


Fig.1. The experimental set-up used to observe external switching of the reflectivity from the InSb. A1 and A2 are apertures.



Time (5 μs/div)

(a)

Time (5 μs/div)

(b)

Fig.2 (a) The CO_2 laser pulse, (b) the reflected signal of the HeNe light that was switched out by the CO_2 pulse.

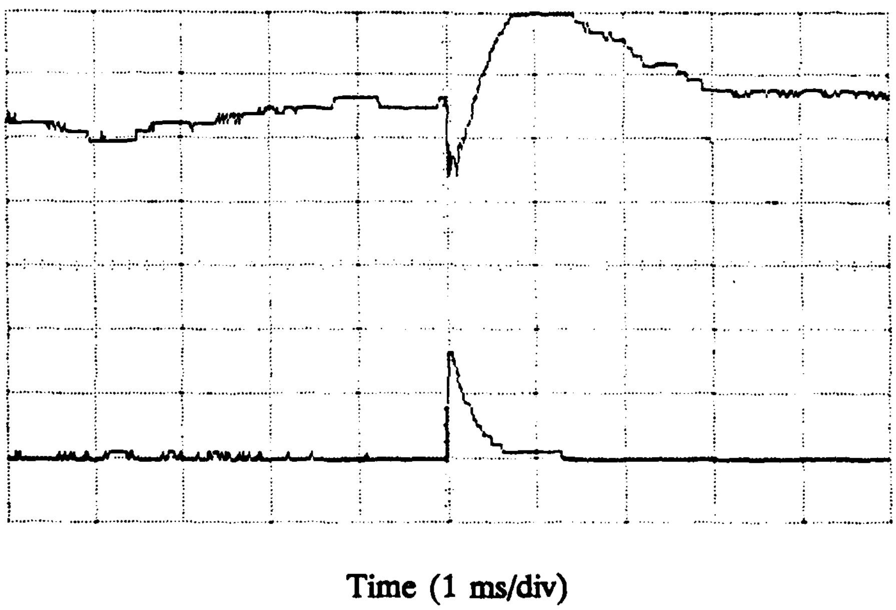


Fig.3 Response of the reflected HeNe signal on the CO_2 laser pulse. The lower trace is the CO_2 pump pulse, the upper trace is the inverted reflected HeNe probe signal.

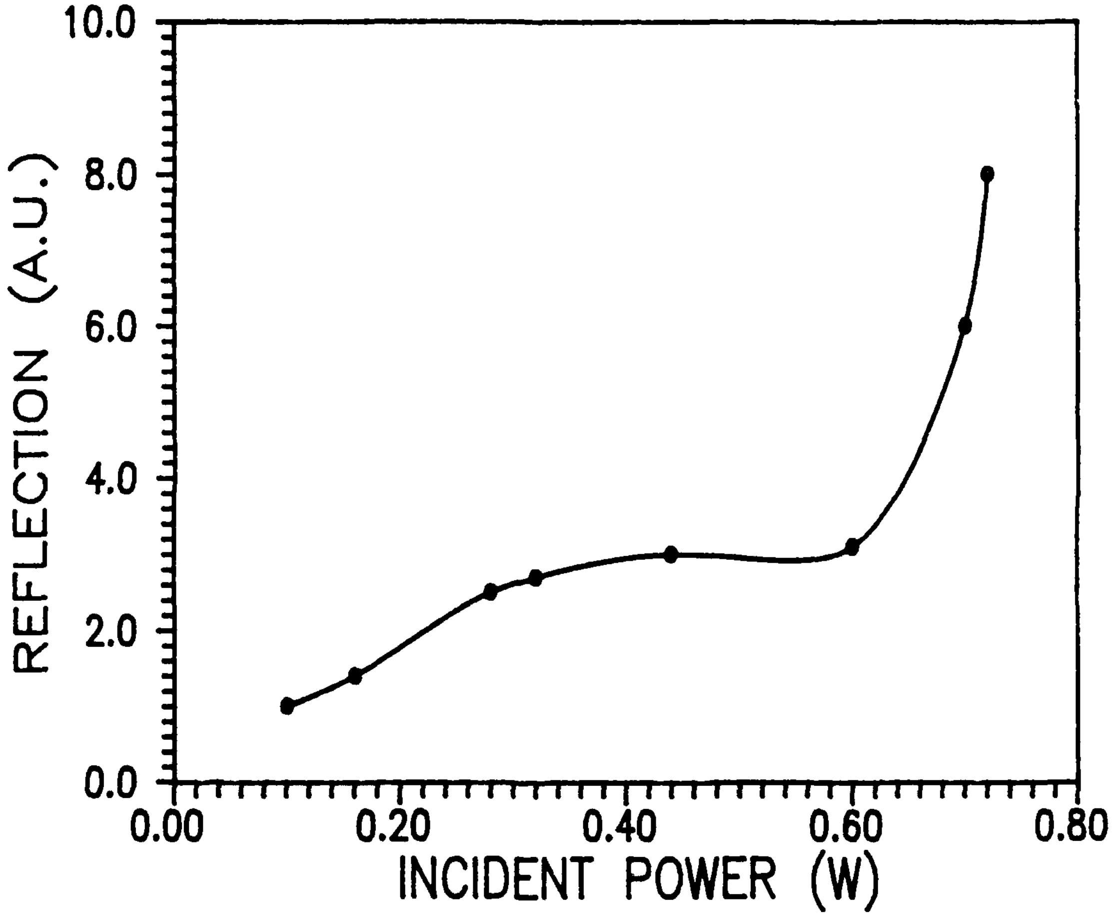
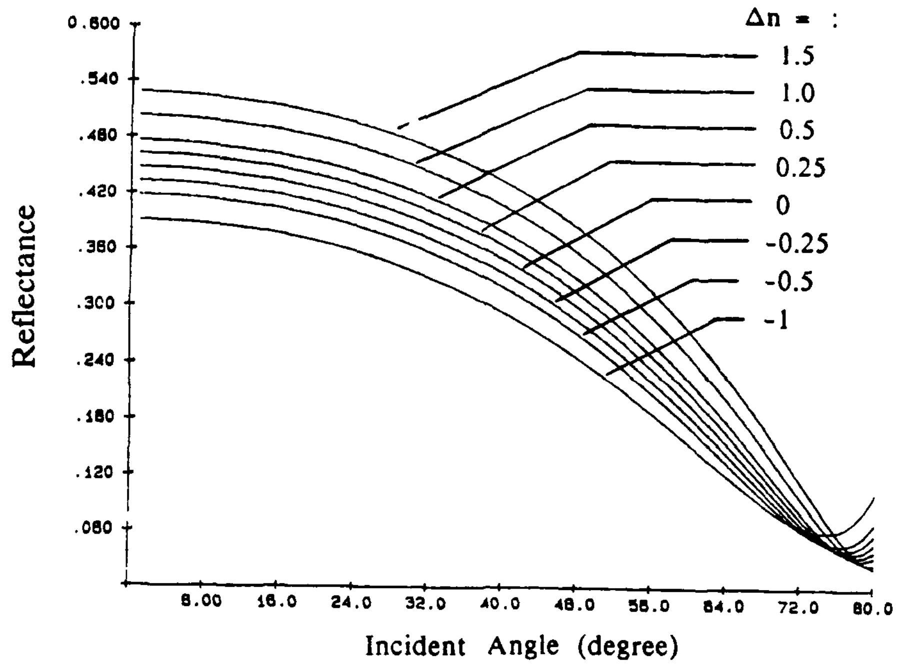
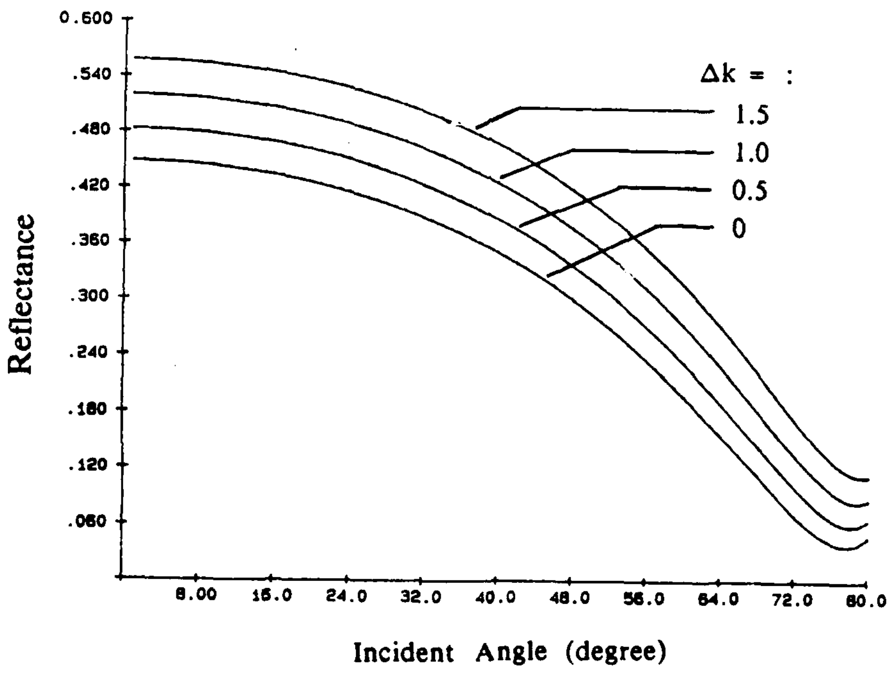


Fig.4 Incidence-reflection characteristic of the InSb surface for cw CO_2 radiation.

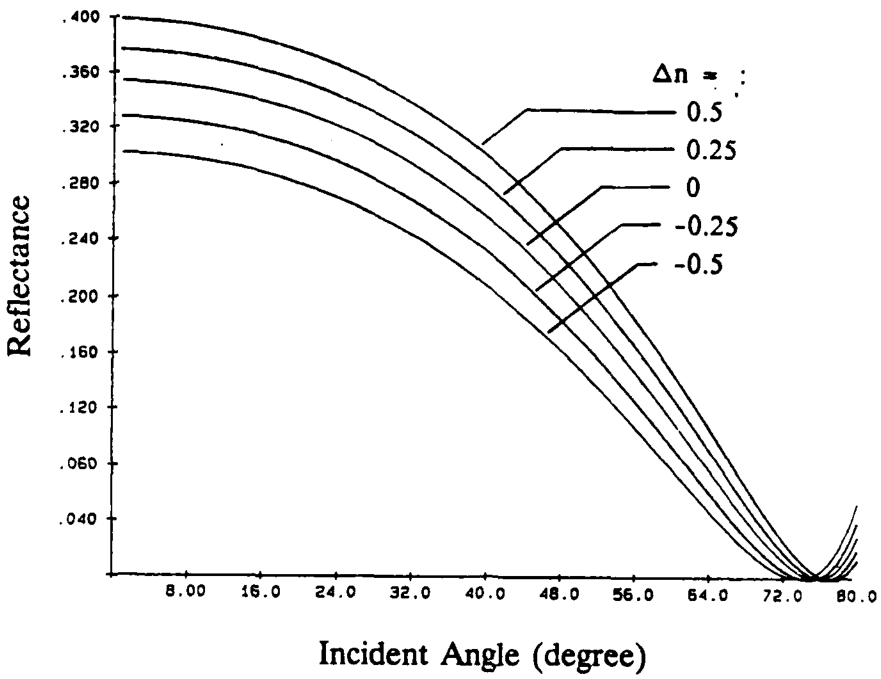


(a)

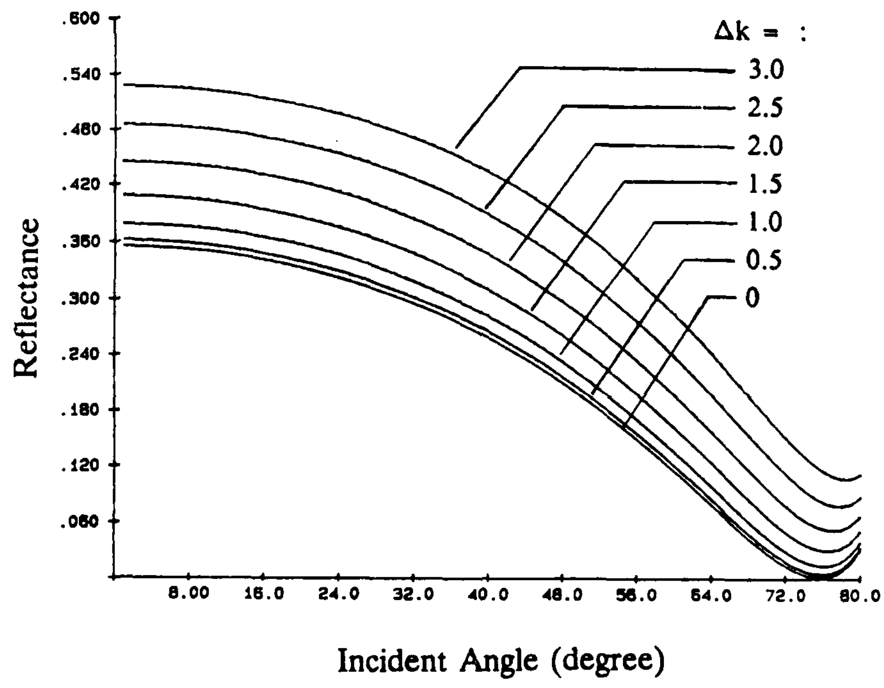


(b)

Fig.5 Plots of reflectance versus incident angle for the wavelength of 6328 Å with (a) different n, and (b) different k, respectively.



(a)



(b)

Fig.6 Plots of reflectance versus incident angle for the wavelength of 10 μm with (a) different n, and (b) different k, respectively.